HEAO 3 Observations of the Galactic Center 511 keV Line

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ABSTRACT

The existence of an intense narrow electron/positron annihilation line from the direction of the Galactic center is unquestioned; however, the source of the positrons remains a mystery. It is believed the line emission has two components: one compact at or near the Galactic center, and the other extended in the equatorial plane of the Galaxy. A compact component is suggested by several reports of intensity variations, including one from our group based on HEAO 3 data. Since the original HEAO 3 analysis, our algorithms have been greatly improved and we have gained a much better understanding of systematic effects which could influence the results. Given the importance of the result and the significantly improved analysis techniques now available, the data have been reanalyzed. For a single point source at the Galactic center, the revised line intensities are $(1.25 \pm 0.18) \times 10^{-3}$ photons cm^{-2} S-l for the fall of 1979 and $(0.99 \pm 0.18) \times 10^{-3}$ photons cm^{-2} S-l for the spring of 1980.

Subject headings: gamma-rays: observations—the Galaxy: center— nucleosynthesis: general

1. Introduction

High-resolution spectroscopy of the 511 keV electron-positron annihilation line provides perhaps the most powerful diagnostic tool in gamma-ray astrophysics. Such annihilation radiation occurs frequently in nature with strong emission observed from solar flares (Chupp 1984), galactic novae (Goldwurm et al. 1992), the Earth's atmosphere (ie Mahoney et al. 1981a), probably Cygnus X-1 (Ling & Wheaton 1989), and, of course, the Galactic center region (see reviews by Lingenfelter & Ramaty 1989; von Ballmoos 1991; Skibo et al. 1992). Detailed spectroscopic observations of the intensity, width, and energy of the annihilation line can provide a wealth of information of the temperature, density, composition, and dynamics of the source region. Furthermore, spectral structure arising from Compton scattering of the 511 keV line can potentially be used to probe the geometry of accretion disks and the physical conditions under which the positrons scatter and annihilate (Lingenfelter & Hua 1991).

Emission at 511 keV from the vicinity of the Galactic center was first reported (Johnson et al. 1972) over two decades ago and has since been observed by numerous experiments on both balloons and satellites. It has been argued (Lingenfelter & Ramaty 1989) that the narrow line emission has two basic components. The first is extended in the Galactic plane with a concentration toward the Galactic center (Share et al. 1988; Purcell et al. 1993). An extended component must exist given the presence of approximately 3 $M_\odot$ of ^{26}Al (Mahoney et al. 1984) distributed throughout the interstellar medium (ISM). The ^{26}Al decays primarily via the emission of positrons which subsequently slow down and annihilate in the ISM, accounting for roughly 15% of the observed 511 keV line flux. The remainder of this extended component can be explained by the decay of other radionuclei created during Galactic nucleosynthesis (Ramaty & Lingenfelter 1979), primarily ^{44}Ti (Woosley & Pinto 1988; Mahoney et al. 1992) and ^{56}Co (Ramaty & Lingenfelter

A second, compact component has been suggested by time variability of the annihilation line intensity (cf. Lingenfelter & Ramaty 1989). The positrons could be created by erratic accretion of material onto a black hole, perhaps the variable source 1E1740.7-2942 which was recently observed by SIGMA to exhibit flaring activity in a broad feature near 0.5 MeV (Bouchet et al. 1991; Sunyaev et al. 1991). In fact radio observations (Mirabel et al. 1992) showed jets symmetric around a core source coincident with the location 1131740.7-2942 as determined by x-ray observations (Skinner et al. 1991). Furthermore, variations of the hard x-ray continuum and of the radio intensity are highly correlated. The observed radio emission is consistent with 1E1740.7-2942 being a strong and variable source of positrons.

Time variability of the narrow 511 keV line was first reported by our group (Riegler et al. 1981), based on analysis of data from the HEAO 3 gamma-ray spectrometer which indicated an intensity decrease from $(1.85 \pm 0.21) \times 10^{-3}$ photons cm^{-2} S–l in the fall of 1979 to (0.65+ 0.27) x 10^{-3} photons cm^{-2} S-* six months later. Balloon observations in the early 1980's also gave a very low intensity (cf Tueller 1993). Although many still believe that a compact source exists, with the possible exception of HEAO 3, no variations in the narrow line intensity have been observed with satellite experiments during long term (weeks to months) monitoring of the Galactic center. In fact, results from both the Gamma-Ray Spectrometer on SMM (Share et al. 1990) and the Oriented Scintillation Spectroscopy Experiment (OSSE) on CGRO (Purcell et al. 1993) are consistent with a constant flux. Conclusive identification of a compact component may well have to await detailed mapping of the 511 keV line distribution by INTEGRAL (Winkler 1991).

Since the original HEAO 3 data analysis, a number of significant improvements to the primary fitting procedure have been developed and tested. We believe that errors from incorrect modeling of the cosmic source distribution now outweigh statistical and instrumental contributions. Given the great improvement in the analysis algorithms, the HEAO 3 data have been reexamined for an assumed point source at the Galactic center.

2. Analysis Methods and Systematic Effects

The HEAO 3 high-resolution gamma-ray spectroscopy experiment consisted of an array of four high purity germanium detectors in an active CsI(Na) anticoincidence shield which provided background suppression and source flux collimation. The shield defined an aperture of about 35° FWHM at 511 keV (Mahoney et al. 1980). HEAO 3 was a scanning mission with a spin period of about 20 minutes. The spacecraft spin axis normally pointed toward the Sun with the gamma-ray experiment mounted to view at right angles to the spin axis. However, for intervals totaling about 14 days in both the fall of 1979 and in the spring of 1980, the spacecraft spin axis was oriented toward a Galactic pole, allowing the experiment to scan directly in the Galactic equatorial plane. For the present analysis, data were analyzed for all scans where the instrument viewing axis passed within about 25° of the Galactic center. This included both normal and Galactic plane scans totaling 21 days in the fall of 1979 (September 23- October 14) and 50 days in the spring of 1980 (February 20- April 10).

The data were analyzed by fitting each scan across the source to a multi-term linear model (Wheaton et al. 1993). Coefficients in the model were estimated, along with their uncertainties, by linear least squares fits done independently for each detector and for each energy channel. Final answers were obtained by weighted averaging over detectors and scans. For this paper, the standard model (alternative models were explored, as discussed below) included a term for a point source at the Galactic center plus terms for three types of background: one prompt, driven by the local cosmic-ray flux, a second from cosmic rays producing secondary gamma rays in the Earth's atmosphere, and finally a constant which includes all long-term activation. For this standard model, the net spectra for a Galactic center point source are shown in Figure 1. Fitting these spectra to a linear background and a Gaussian line with a fixed energy and width gives net line intensities of $(1.25 \pm 0.18) \times 10^{-3}$ and $(0.99 \pm 0.18) \times 10^{-3}$ photons cm^{-2} s^{-1} in 1979 and 1980, respectively.

Numerous alternate linear models and variations in the data selection criteria were investigated to study possible systematic effects which could influence the line parameters. A much more thorough study has been made possible by the recent transfer of the entire

HEAO 3 data analysis system to a Sun SPARCstation with a consequent factor of 50 increase in processing speed.

The standard analysis involves data selection based on parameters such as the limit on the scan angle of the viewing axis which controls how much of the 20-minute scan will be included in a fit. It can be varied from a relatively restricted region around the source (scan angle limit = $\pm 60°$) to the entire scan (scan angle limit = $\pm 180°$). The dependence of the line flux on the scan angle limit, with all other variables fixed, is shown in Figure 2a, The plotted data are the fitted intensities for spectra similar to (and including) those shown in Figure 1. With the possible exception of the first data point, the line intensities are independent of this selection criterion. Although the statistical uncertainty decreases slowly with increasing scan angle, for conservatism the baseline limit was set to 150°.

A similar study showed the net line flux is also independent of the limit on the zenith angle of the viewing axis (Figure 2b). It should be noted, however, that the Earth's atmosphere is a strong source of narrow 511 keV line emission. Models which do not include this component do show a significant dependence on the zenith angle limit beyond about 100°, as might be expected. For the standard model, the zenith angle limit was conservatively set at 110°.

The net 511 keV line flux is also insensitive to the values of the other selection criteria investigated, further increasing our confidence that the results are relatively free of systematic errors. These criteria included the primary cosmic-ray intensity as represented by the McIlwain L parameter, the charged particle background count rate as measured by a plastic anticoincidence detector, and the time since the last spacecraft passage through the South Atlantic Anomaly (SAA). For the standard model, data were selected for L ≤ 2.0, a charged particle rate $\leq$ 1000 counts S-l, and time since the last SAA passage ≥ 500 s.

3. Results

The spectra obtained with the standard model, shown in Figure 1, represent our best estimate of the true Galactic center emission, assuming the emission arises from a single point source. Although the plotted spectra correspond to the sum of both the normal and Galactic plane scans, the data for the two modes of operation have been analyzed separately with the results listed in Table 1. It is evident that for each observational period, the fitted line flux for the Galactic plane maneuver is consistent with that for the normal scans. Furthermore, although there is still a decrease in line flux from the fall of 1979 to the spring of 1980, the four independent measurements are also consistent with a constant flux.

While we believe the present line fluxes are better estimates of the true cosmic emission, the results are somewhat at odds with our previous work (Riegler et al. 1981), Most of the differences can be explained by the following, in approximate order of significance:

(a) better modeling of the orbital background variations arising from geomagnetic latitude changes,

(b) analysis based on the scan-by-scan subtraction of the background for better removal of systematic errors (Wheaton et al. 1988),

(c) inclusion of an atmospheric background component, and

(d) better values for the instrumental angular response, energy resolution, and energy calibration.

The largest change arises from an improved modeling of the orbital background variations, based on the germanium detector ULD (> 10 MeV) count rate (Wheaton et al. 1993). Inclusion of a component representing the Earth's atmosphere also reduces systematic errors and allows a larger limit on the zenith angle selection criterion. It should also be emphasized that the line flux originally reported for 1979 was based on Galactic plane scans only whereas the current analysis has been done separately for both the normal and Galactic plane scans (Table 1). For the 1980 data, both the current and the original analyses were carried out for both observational modes.

Potential errors arising from the inclusion in the model of other cosmic point sources, such as Cygnus X-1, Aql X-1, and GX339-4, were also investigated. When Cyg X-1 is added, the calculated Galactic center 511 keV line fluxes are (1.48 ± 0.20) x 10^{-3} and (1.03 ± 0.20) x 10^{-3} photons cm-' s^{-1} for the 1979 and 1980, respectively (Table 2). The addition of other sources, including fictitious ones in apparently empty regions, also gave variations of up to roughly 1 σ in the net Galactic center line emission, While the inclusion of Cyg X-1 in the model might be justifiable given the reported measurement of a narrow 511 keV line in its spectrum (Ling & Wheaton 1989), there seems to be no *a priori* reason for including other point sources. It may well be that the fluxes attributed to point sources indicate that the true cosmic distribution of 511 keV line emission is extended in the Galactic plane. At any rate, the variations in the Galactic center line flux of about 0.2 x 10^{-3} photons cm^{-2} s^{-1} should be indicative of the systematic uncertainties in the point source flux.

Models were also investigated with both a point source at the Galactic center and an extended Galactic component concentrated toward the Galactic center (Purcell et al. 1993). For the highly peaked nova distribution (Skibo et al. 1992), the fitted errors on the model components are very large, as expected, since a point source and an extended component highly peaked at the same place look very similar in the 35° field-of-view of the HEAO 3 experiment. Even with the broader CO distribution, the errors in both components increase to the point where no meaningful conclusion can be drawn regarding their relative strengths.

A possible low energy "tail", or step change in the continuum emission at 511 keV has been noted during several GRIS balloon observations (Leventhal et al. 1993). There is little evidence for such a tail in the spring 1980 (Figure lb), however, a possible step, with a magnitude comparable to that seen by GRIS, is suggested for the fall 1979 spectrum. However, the study of the continuum is beyond the scope of the present work except for its possible influence on the fitted line flux. A cursory examination shows that a step change in the continuum would have a small (few percent) effect on the line flux for either observation period, For all spectral fitting, the line energy and width were based on detailed calibration of the instrument response, and on instrumental background spectra obtained during the source observations. The line widths include the effects of radiation damage (Mahoney et al. 1981b) which caused their fitted values to increase from about 3.5 keV FWHM in the fall of 1979 to about 7.5 keV FWHM in the spring of 1980. Unlike the line intensities, the current analysis confirmed the previously reported (Riegler et al. 1981) values for the cosmic line energy, (510.92 $\pm$ 0.23 keV), and intrinsic width, (1.6 + 0.9, –1.6) keV FWHM.

4. Summary and Conclusions

The present work reexamined the earlier HEAO 3 analysis of narrow 511 keV line emission from the Galactic center. Since the original results were published (Riegler et al. 1981), a far more powerful data analysis system has been developed, resulting in a significant decrease in both the systematic and statistical uncertainties. In the current work we have concentrated on a model containing a single point source at the Galactic center because (a) it is the one used by Riegler et al. (1981), (b) it allows direct comparison with SMM observations, and (c) it is simple. For this model, the current estimates of the net galactic center line fluxes are $(1.25 \pm 0.18) \times 10^{-3}$ and $(0.99 \pm 0.18) \times 10^{-3}$ photons $cm^{-2} s^{-1}$, for the fall of 1979 and the spring of 1980, respectively. While there is still a decrease in the intensity for 1979 to 1980, the significance is lower than originally reported and the data are consistent with a constant intensity.

When point sources representing both the Galactic center and Cyg X-1 are included in the model, the fitted value of the Galactic center emission increases by about 1σ in the fall of 1979, but remains inchanged in the spring of 1980. Although the intensity decrease from 1979 to 1980 is more significant when Cyg X-1 is added to the model, the data are still consistent with a constant intensity. Inclusion of other point sources in the Galactic plane resulted in similar variations in the calculated Galactic center line flux, leading us to conclude that the systematic uncertainty arising from improperly modeling the cosmic emission is approximately 0.2 x 10^{-3} photons cm^{-2} s^{-1}, about the same as the statistical uncertainty. An examination of extended distributions is in progress and will be completed shortly.

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Scan Mode	Fall 1979	Spring 1980	Total
Galactic Plane	1.32 ± 0.20	0.91 ± 0.26	1.17 ± 0.16
Normal	1.01 ± 0.38	1.07 ± 0.25	1.06 ± 0.21
Total	1.25 ± 0.18	0.99 ± 0.18	1.13 ± 0.13
Riegler et al. 1981	1.85 ± 0.21[a]	0.65 ± 0.27	

Table 1: Net Galactic center 511 keV line flux, in units of 10^{-3} photons cm^{-2} s^{-1}, for a point source model with zenith angle $\leq 110°$ and scan angle $\leq 150°$.

[a] Galactic plane scans only.

Scan Mode	Fall 1979	Spring 1980	Total
Galactic Plane	1.61 ± 0.22	1.06 ± 0.29	1.41 ± 0.18
Normal	1.05 ± 0.41	1.01 ± 0.27	1.02 ± 0.23
Total	1.48 ± 0.20	1.03 ± 0.20	1.26 ± 0.14

Table 2: Net Galactic center 511 keV line flux, as in Table 1, but with Cyg X-1 added to the model.

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Fig. 1.— The net Galactic center spectrum near 511 keV observed by HEAO 3 in (a) the fall of 1979, and (b) the spring of 1980. The spectra include normal and Galactic plane scans and were obtained with the scan angle and zenith angle limits set at 110° and 150°, respectively. The line broadening between the fall of 1979 and the spring of 1980 arises from radiation damage to the germanium detectors.

Fig, 2.— The net Galactic center 511 keV line flux calculated (a) as a function of scan angle limit from the Galactic center with the zenith angle limit set to 110°, and (b) as a function of zenith angle limit with the scan angle limit set to 150°. Measurement in the fall of 1979 are indicated by x's while the spring 1980 data are shown as open circles.

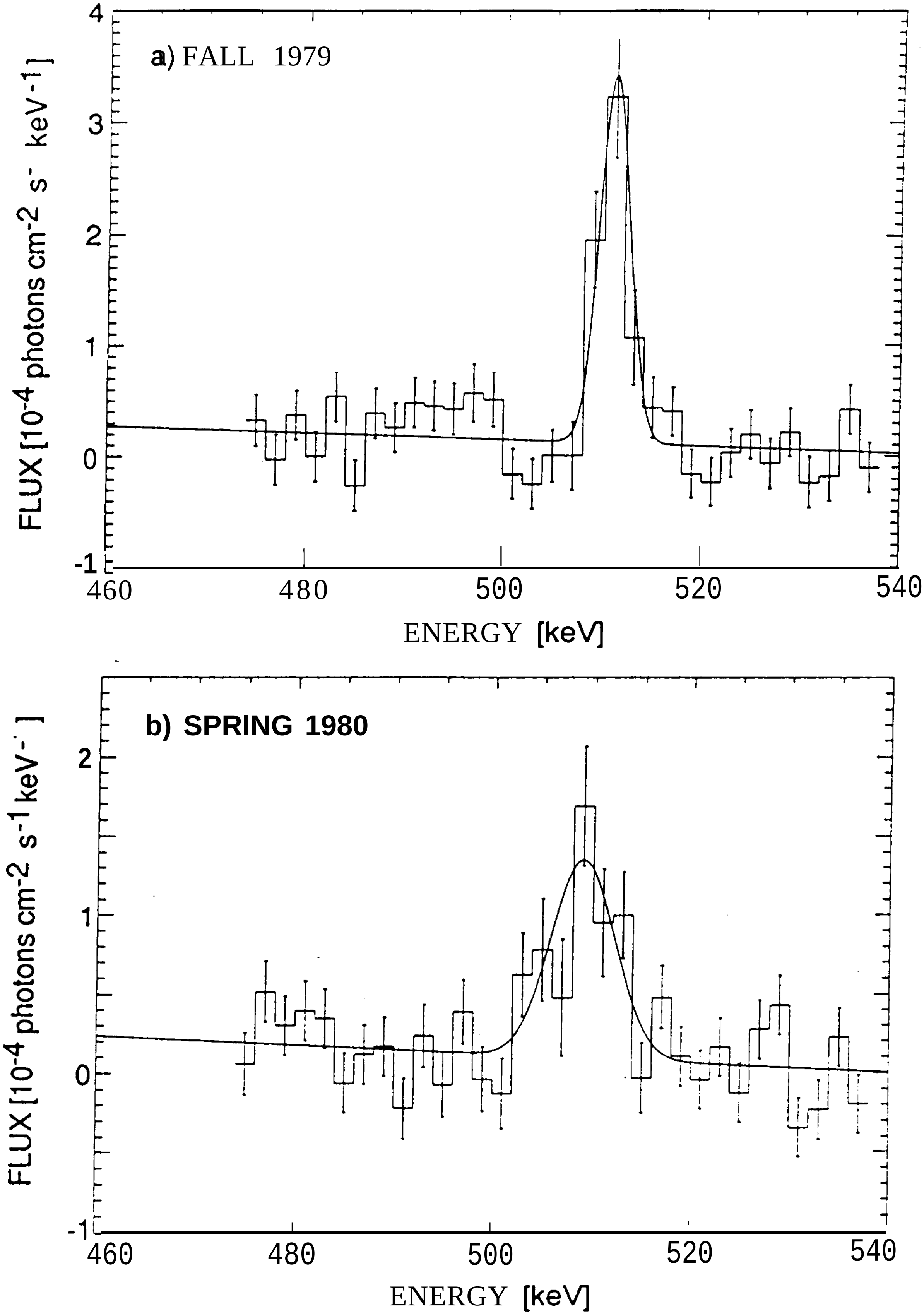
a) FALL 1979
FLUX [10-4 photons cm-2 s- keV-1]
ENERGY [keV]
b) SPRING 1980
FLUX [10-4 photons cm-2 s-1 keV-1]
ENERGY [keV]

Figure 1

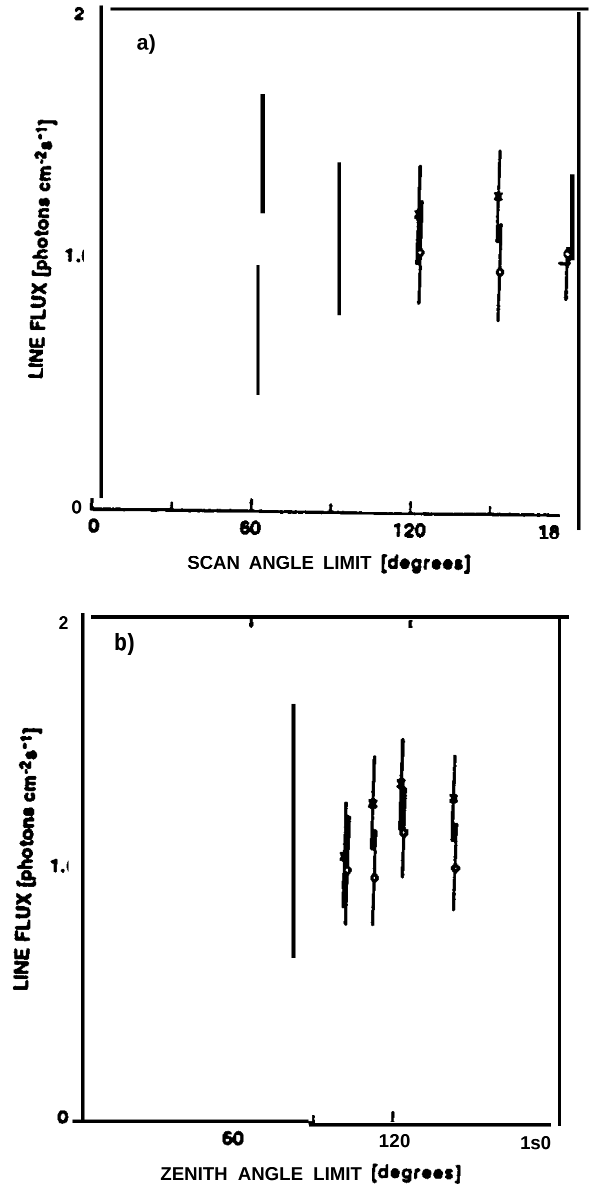
a)
LINE FLUX [photons cm-2s-1]
SCAN ANGLE LIMIT [degrees]
b)
LINE FLUX [photons cm-2s-1]
ZENITH ANGLE LIMIT [degrees]

Figure 2